THE INFRARED BACKGROUND: THEORY

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1. INTRODUCTION

The infrared region of the spectrum is a very interesting and important one for the study of extragalactic backgrounds, both galaxian and pre-galactic. This review concentrates on backgrounds from protogalaxies and galaxies. Detailed discussions of many possible pm-galactic backgrounds have recently been presented by Bond, Carr and Hogan (1986, 1991); see Carr (1992) for a recent review of these and Wright *et* al. (1 993) for a summary of how well some of them have fared in light of the most recent COBE observational results. 1 will concentrate on the approximate wavelength range 10 to 500μm since both the near-infrared and the submillimeter range arc discussed by others.

The infrared spectral region is a good place to look for detectable backgrounds from the integrated light of galaxies and protogalaxies for several reasons. First, young galaxies and protogalaxies may have been relatively much more luminous at far-infrared wavelengths, compared to the optical-US, than galaxies at the present epoch. Metallicity can increase rapidly during the early evolution of galactic systems, and if dust formation follows suit the dust optical depth and the far-infrared luminosity can rise dramatically at the expense of the obscured optical-UV luminosity (Wang 1991a,b; Lonsdale 1992; Mazzei, De Zotti and Xu 1993).

Figure 1 illustrates a second reason for the importance of the infrared region to background studies of galaxies and protogalaxies: the prominent "windows" between the various foregrounds and the cosmic microwave background radiation (CMB). This figure is similar to several which have been shown already at this meeting, depicting the intensity νI_ν in W/cm^2/sr. The main foregrounds in the infrared spectra] region shown in Figure 1 arc the zodiacal light which peaks near 1μm and falls into the far-infrared, the interplanetary dust (IPD) emission peaking near 10μm, and the interstellar dust (ISD) peaking beyond 100μm. There are two main infrared "windows": one near 3μm and the second at about 300/Ire."

It is not simply the existence of these windows that marks their importance, but also the fortunate chance that they happen to coincide very nicely with the two prominent peaks in the spectral energy distributions of moderate-to-high redshift galaxies: the stellar spectral energy distribution of nearby galaxies peaks near 1μm, thus moves into the 3μm window with increasing redshift, while the dust rc-emission peak of ISM-rich galaxies peaks near 60 to 100μm, moving into the 300μm window with increasing redshift. Thus there is a rich hunting ground for the integrated stellar light of galaxies in the near-infra.rcd window, and another one for the dust emission of galaxies in the fi~r-infrared window. Conversely it will be difficult to ever]nca.sure the integrated light of galaxies or protogalaxies in the 5 to 30μm region unless spacecraft can be sent to the more distant reaches of the solar system where the interplanetary dust emission is much reduced.

Another reason why the infrared spectral region is one of the most valuable for studying the background light due to galaxies is that there is a strong positive far-infrared K-correction with redshift. Unlike the situation in the UV through near-infrared spectral region, the energy distributions of galaxies at $\lambda \gtrsim 80\mu m$ fall with increasing wavelength with a very steep dependence on λ, therefore at longer wavelengths than this the 1{-correction can almost counter the cosmological effects of luminosity distance and surface brightness dimming so that the apparent flux density at a fixed observing frequency has little dependence on distance. The same effect holds to a more limited extent in the 3-- 20μm region.

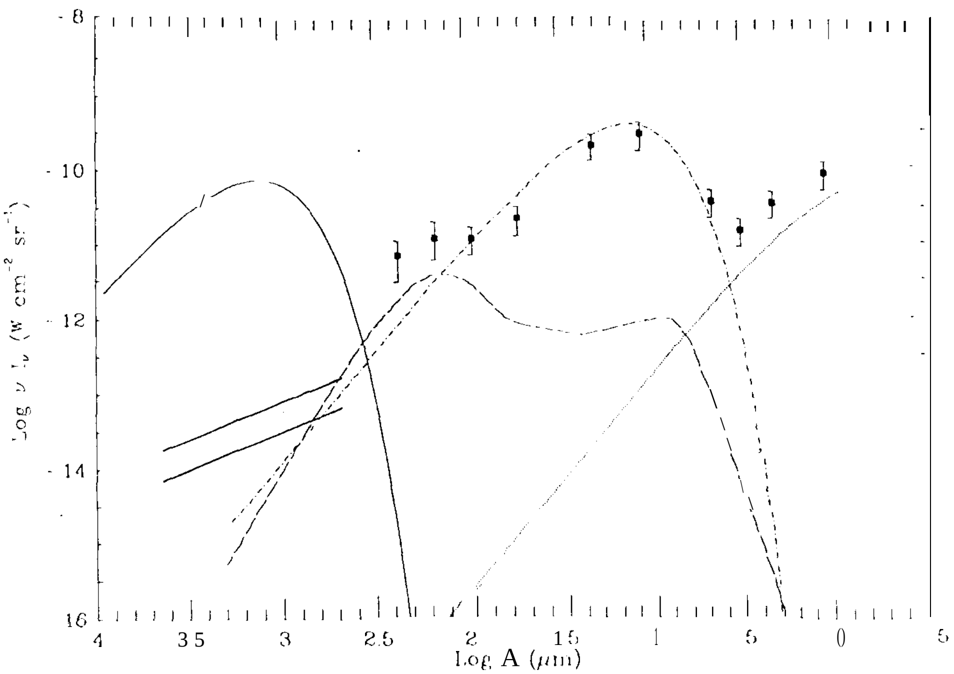

Figure 1. The infrared fore.grou]lds and COBE limits. The solid curve is the cosmic microwave background (CMB) radiation, and the other three curves are various foregrounds, as derived by Beichman and Helou (1991; C. Beichman, private communication): the dotted curve is the reflected solar zodiacal emission, the clot-dash curve the thermal emission from interplanetary dust, and the dashed curve the thermal emission from interstellar dust scaled to a brightness of $I_\nu(100\mu m) = 1$ MJ y/sr, which is representative of the typical sky brightness in regions of the weakest cirrus emission at high galactic. latitude. The lower snort heavy solid line illustrates the maximum deviation from the CMB measured by FIRAS (Mather *et al.* 1993), 3.4×10^{-8} erg cm^{-2} s^{-1} sr^{-1} cm, which is 0.03% of the peak of the CMB spectrum, while the upper line represents an estimate of this maximum deviation adopting a more conservative galactic. foreground subtraction]] (see text). The solid squares depict the DIRBE limits at the north ecliptic pole, as discussed by M. Hauser note that these do not include any subtraction of the galactic or zodiacal foregrounds.

Finally, it is possible that intervening galaxies may produce sufficient obscuration to eliminate optically-selected background quasars from flux-limited samples (Ostriker and Heisler 1984; Wright

1990; Fall and Pei 1993), especially if there has been strong evolution of the dust optical depth (Wang 1991a,b; Mazzei *et al.* 1993). It is therefore also possible that such an effect will obscure background young galaxies and protogalaxies. At far-infrared wavelengths, not only will the obscuration be low enough to be insignificant, but the dust which is responsible for extinguishing the optical-UV light will re-emit this light in the far-infrared and submillimeter.

Mike Hauser has given us an excellent summary of the observational results on the infrared backgrounds. For the purposes of my discussion of the theoretical backgrounds expected from galaxies and protogalaxies, I summarise on Figure 1 the most recent observational limits from DIRBE and FIRAS on COBE. As Mike has described, the DIRBE data do not yet include any foreground subtraction, pending the very difficult task of modelling the galactic emission in detail. The spectacular FIRAS results of Mather *et al.* (1993) do include a galactic foreground subtraction, and have a maximum deviation from the CMB black body spectrum in the 2 - 20 cm^{-1} region of 0.03% of the peak of the CMB spectrum. However, as Wright *et al.* (1993) have noted, this foreground subtraction is not appropriate for modelling the cosmological backgrounds due to the integrated light of galaxies because the background itself is expected to have a spectral shape similar to that of the galaxy, thus the "galactic foreground" that has been subtracted could include some cosmological background. Wright *et al.* used a $\csc|b|$ method of galactic foreground subtraction to avoid this problem, and from their integrated galaxy light model fits I estimate a maximum deviation of about twice that inferred by Mather *et al.*. This is illustrated by the upper of the two heavy solid lines in Figure 1.

2. INTEGRATED INFRARED EMISSION OF GALAXIES

IRAS has shown us that the far-infrared emission of galaxies in the local universe constitutes a large fraction, $\sim 30\%$, of the total energy output of normal galaxies, and that for some starburst and active galaxies the far-infrared fraction can be much higher (see Lonsdale 1992 and references therein). It follows by analogy to derivations of the expected integrated light in the optical band (*eg.* Partridge and Peebles 1967) that the integrated light of galaxies in the infrared region can be expected to be at least a few percent of the peak of the CMB. Hacking, Condon and Houck (1987) found evidence for strong luminosity and/or density evolution of IRAS galaxies, at a rate comparable to that of quasars, which further enhances the expected integrated background radiation (see also Franceschini *et al.* 1988b; Lonsdale and Hacking 1989; Lonsdale *et al* 1990; Saunders *et al.* 1990; Hacking and Soifer 1991).

The simplest kind of model for the integrated emission of galaxies involves taking a local luminosity function (LF) and a functional form for the evolutionary law, and extrapolating backwards in time to match the observed flux and redshift distributions of deep galaxy samples in a particular wavelength band. The model distributions are then integrated over flux and redshift, to some maximum redshift, z_{max}, to derive a background intensity. In many models the entire luminosity function is fixed in shape and it translates *en masse* in luminosity and/or density at the given rate. Such models are called translational models, and they were originally proposed for the evolution of radio sources and quasars. The physical interpretation of such evolution involved an increasing luminosity of AGN with lookback time for luminosity evolution, or an increasing fraction of galaxies possessing AGN at earlier times for density evolution. In the context of far-infrared bright galaxies, power law translational evolution would describe an increasing luminosity of starbursts and/or AGN with lookback time, or an increasing fraction of galaxies undergoing starburst episodes and/or AGN events with lookback time. Thus this kind of evolution is not well suited for describing the recently popular merging scenarios, in which smaller galaxies merge to form larger ones - such scenarios implicitly involve evolution of the shape of the luminosity function.

A summary of the parametric. models of the far-infrared background that have been published based on translation] evolution is given in the upper panel of Table 1. The wavelengths or wavelength range modelled, the cosmology, and z_{max} adopted by these various authors is given. The parameters α, β, κ and Q define the parametric form of the assumed evolution behavior of the LF with redshift, as follows:

$$L(t) = L(t_0)\,(1+z)^{\alpha} \tag{1}$$

$$\rho_{co}(t) = \rho_{co}(t_0)\;(1+z)^{\beta} \tag{2}$$

describing power law luminosity and density evolution, respectively, where ρ_{co} is the co-moving density, and:

$$L(t) = L(t_0)\;e^{[\kappa\,(1-(t(z)/t_0))]} \tag{3}$$

for exponential luminosity evolution. For $\Omega=1$, $(t(z)/t_0) = (1+z)^{-3/2}$ defining the relation used by Oliver *et al.* (1992): $L(t) = L(t_0)\exp\{2/3Q[1-(1+z)^{-3/2}]\}$.

For the first four models in Table 1 all galaxies comprising the LF are allowed evolve at the same rate, while the model of Franceschini *et al.* (1991) allows for three galaxies types to evolve at different rates. The mode] of Treyer and Silk is different in nature from the others in that they do not allow the luminosity function of "normal" galaxies to evolve with time, but acid a new population of dwarf galaxies whose characteristic space density, ϕ^* (Mpc^{-3}), is the parameter that evolves:

$$\phi^*_{dw} = 6.0\times10^{-2}\left(\frac{0.7}{z}+1\right)^{-1}h^3 \tag{4}$$

where $h = H_0$ in units of 100 km/s/Mpc. This model is designed to explain the steepness of the observed blue number counts of galaxies with a population of dwarf galaxies which is present at z = 0.7 but has faded to invisibility by the current epoch. Treyer and Silk also investigate a model based on the number density evolution of dark matter halos in a cold dark matter scenario, which predicts a large adundance of low-mass halos. The integrated background light produced by this model is very similar to that, of the blue dwarf model described by equation (4).

A different kind of model assumes that the evolution with lookback time of galaxies in the far-infrared is principally due to the natural evolution of their stellar populations and interstellar medium, without necessarily invoking dramatic starburst or AGN events. The most sophisticated kind of model involves population synthesis using stellar photometric and chemical evolution prescriptions to model in detail the spectra] energy distributions of various galaxy types as a function of time. The evolutionary behavior of models of this type is usually dictated by an assumed dependence of the star formation rate on some power of the gas mass or density. As for the purely parametric LF translational models, the synthesis models are matched to the flux and redshift distributions of deep galaxy samples and then integrated to derive backgrounds.

Population synthesis modelling of evolving galaxies is a very active field in the UV through near-infrared bands, but it is less well developed at far-infrared wavelengths because the dust re-emission of stellar photons is an extra dimension which most modelers have yet to tackle. The population synthesis models of Mazzei, Xu and de Zotti (1992) and Mazzei, De Zotti and Xu (1993) are the first to fully incorporate the re-emission of starlight by dust within galaxies. These closed box models incorporate chemical evolution, thus at early epochs the dust content grows with time as

Table 1: Far-Infrared Evolutionary Models

Model	λ (μm)	H_0	Ω	z_{max}	α,β,κ,Q	Figure
Weedman 1990	100	75	0.1	4	α=2.5	4
Hacking and Soifer 1991	25, 60, 100	75	1	0.5 3	β=4 α=2,3	4
Beichman and Helou 1991	10-1000	40-100	0-1	1-5	β=2,4	4
Oliver *et al.* 1992	4-1500	50	1	1-7	α=3.15 β=6.7 Q=3.2	5
Franceschini *et al.* 1991	12-1000	50	0.1	5	normal galaxies: κ=0 starbursts: κ=3.2 AGN: κ=2.5	4
Treyer and Silk 1993	12-550	50	1		see text	4
Wang 1991b	20-1000	50	1	2,5,20		6
Franceschini *et al.* 1993	20-1000	50	1	4.5		6

the metallicity increases with the return to the interstellar medium of enriched gas from evolved stars. The dust optical depth reaches a maximum and some point in time and then declines again as star formation gradually uses up the ISM.

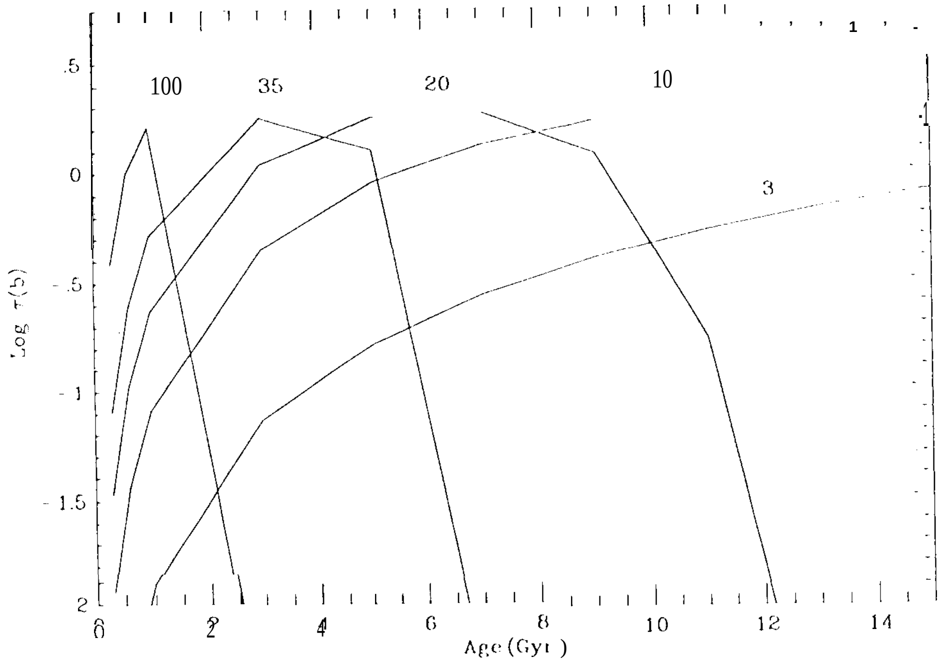

Figure 2. optical depth in the blue from Mazzei *et al.* (1992). The curves are labelled by the initial star formation rate ($M_\odot$/yr).

The rate of change of the dust opacity is a function of the initial star formation rate, which is largest for the earliest type galaxies and smallest for the latest types. The behavior of τ with time is illustrated for several galaxy types in Figure 2: a much more rapid relative far-infrared/optical-UV evolution is expected with lookback time for early type than for late-type systems, because the latest type systems are still reaching their peak optical depth at the present epoch. Late-type systems in the local universe do indeed emit similar amounts of energy in the optical-UV and the far-infrared, whereas ellipticals now emit only a very small fraction of their energy in the far-infrared,

In Figure 3, I reproduce a figure from Mazzei and de Zotti (1993), which shows model spectral energy distributions for a range of ages for elliptical galaxies, compared to the observed data for the high redshift IRAS galaxy F10214+4724 (see Section 3.1 for a discussion of this object). The oldest of these models represents a present day elliptical, and matches observations of local ellipticals well (Mazzei *et al.* 1993). This figure clearly illustrates the expected very strong evolution in the shape of the spectral energy distribution (SED), with a far higher percentage of the total energy emerging at far-infrared wavelengths at early times than today.

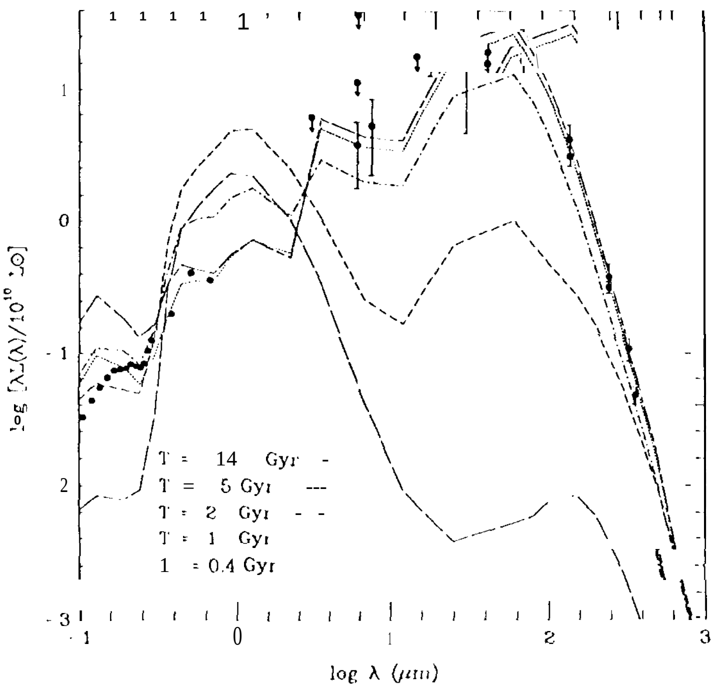

Figure 3. Evolution of the spectral energy distribution of an elliptical galaxy (Mazzei *et al.* 1993) compared to the observed spectrum of IRAS F10214+4724 at $z = 2.286$ (reproduced from Mazzei and De Zotti 1993). This model has a Salpeter (1955) IMF with a lower mass limit of 0.5 $M_\odot$, a star formation rate proportional to the gas fraction to the 0.5 power, and dust-to-gas ratio proportional to the metallicity. The data are from Rowan-Robinson *et al.* (1993), Downes *et al.* (1992) and Telesco (1993).

Two models based on the natural chemical and photometric evolution of stellar populations and interstellar medium are summarised in the lower panel of Table 1. Franceschini *et al.* (1991) have used the models of Mazzei *et al.* to predict the cosmological Background due to evolving galaxies in the near and mid-infrared, however in the far-infrared region they revert to a power law parametric approach similar to those discussed above. This approach is improved in Franceschini *et al.* (1993), who extend the synthesis modeling to the far-infrared. They obtain good fits to the local 60μm counts with their model, due for the most part to the strong dust evolution of early-type systems. Chokshi *et al.* (1993) have used the models of Mazzei *et al.* (1992) to simulate deep blue and near-infrared galaxy images, and Chokshi *et* al. (1994, in preparation) will extend their approach to a full spectral synthesis modelling at far-infrared wavelengths.

Wang (1991a,b) has also considered the evolution of the dust and the far-infrared emission from disk galaxies with time, and their contribution to the far-infrared background. Taking an analytical rather than a population synthesis approach, Wang derives the chemical evolution for a prompt initial enrichment (PIE) model and also for an accretion model, and the subsequent evolution of the interstellar dust, which he argues forms principally in molecular clouds. Wang finds that the dust content of young disk galaxies can be up to 4 times larger than today, and the far-infrared luminosity can be two orders of magnitude greater. The PIE model predicts much stronger backgrounds than the accretion model because it shows strong evolution of the dust mass.

2.1 Model Results

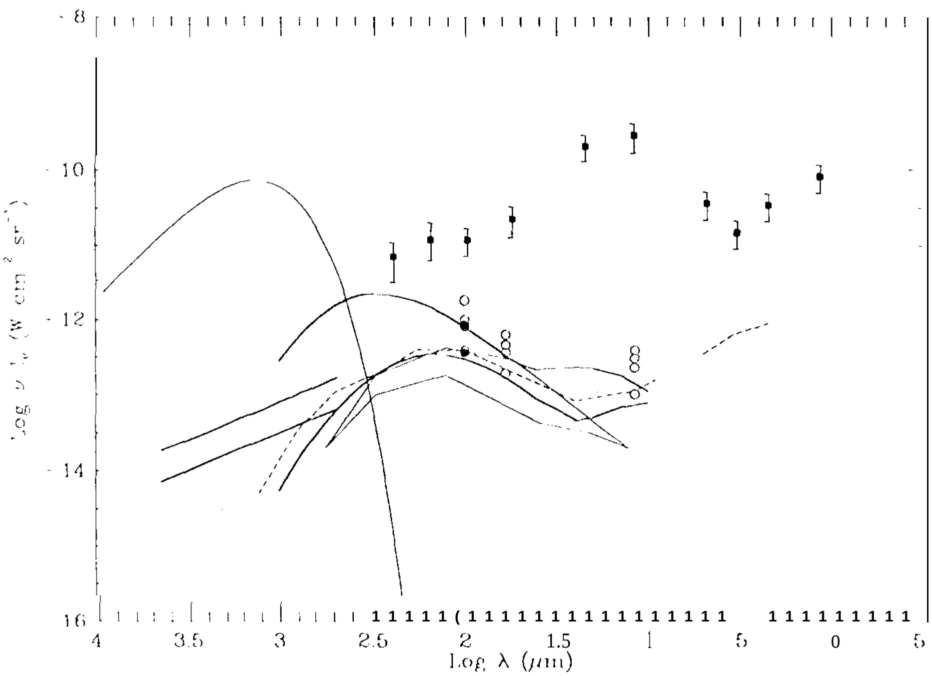

Figure 4. Comparison of various translational evolution models for the integrated light of galaxies to the COBE data. Heavy solid lines - Beichman and Helou (1991) no-evolution model, H_0= 40, q= 0.25 (lower), and density evolution model, β= 4, H_0= 100, q= 0 (upper); Short dashed line Franceschini *et al.* (1991) evolving model, as summarised in Table 1; Light solid lines Treyer and Silk (1993) no-evolution and evolving model (equation 4); Open circles Hacking and Soifer (1991); Solid circles - Weedman (1990).

The results of the various parametric LF translational evolution models for the infrared background emission are summarised in Figures 4 and 5. The Beichman and Helou (1991) models selected for this figure bracket all their models, and incorporate an improved treatment of the energy distributions of local galaxies compared to the models in the published paper (G. Helou, private communication).

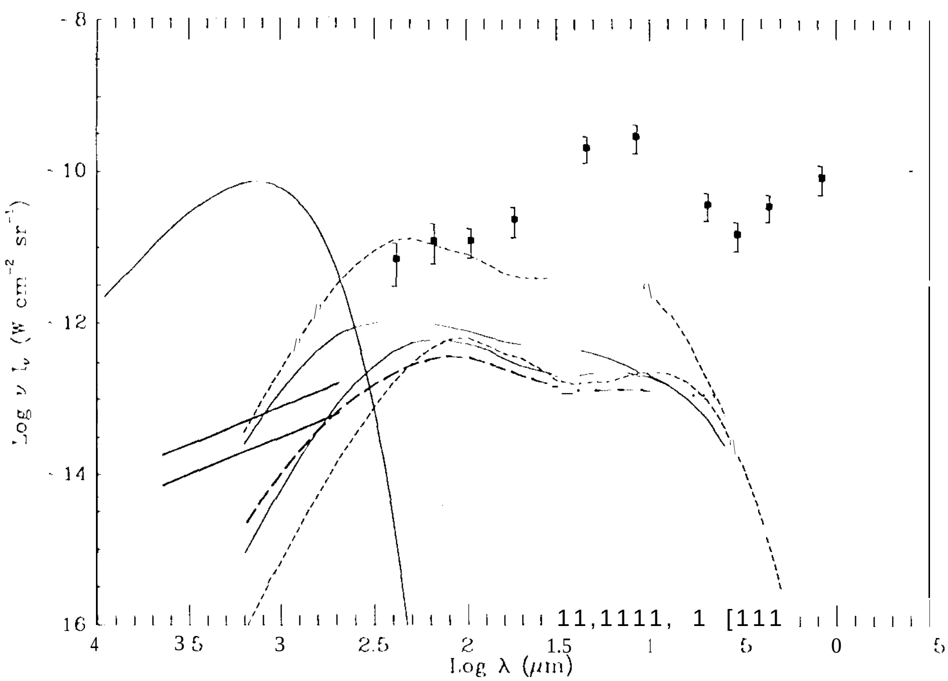

Figure 5. Comparison of Oliver *et al.*'s (1992) translational evolution models for the integrated light of galaxies to the COBE data. Dashed lines - density evolution, z_{max} = 1.0 (lower) and z_{max} = 2.16 (upper); Heavy dashed line- exponential luminosity evolution, $Q = 3.2$, z_{max} = 6.94; Light solid lines power law luminosity evolution, $\alpha = 3.15$, z_{max} = 2.16 (lower) and z_{max} = 5.31 (upper).

Most of the parametric models summarised in Table 1 do not conflict with the currently available DIRBE limits, however the higher evolutionary rates and the higher values for z_{max} are constrained by the longest wavelength DIRBE limits, in particular the higher z_{max} density evolution models of Oliver *et al.* are inconsistent with the DIRBE limits.

The FIRAS distortion limits provide a much stronger constraint, particularly the lower line with the galactic foreground removed by Mather *et* al.. As noted above, however, this limit may be too stringent for comparison to the evolving galaxy models, since a portion of the "galactic foreground" that has been removed by Mather *et al.* (1993) may be part of an isotropic extragalactic background due to the integrated light of galaxies (Wright *et al.* 1993). Even our approximate estimate of the FIRAS limit using Wright *et al.*'s more conservative $\csc|b|$ galactic foreground subtraction constrains the evolving models quite strongly, *ruling out* the parametric power luminosity evolution models with values of α high enough to fit the 60μm number counts ($\alpha \sim 3 - 4$). Thus if pure power law luminosity evolution is the explanation for the steepness of the local universe 60μm number counts, then this evolution cannot continue to cosmological distances without severely violating the FIRAS distortion limits. There is some evidence that power law luminosity evolution with $\alpha > 2$ is also ruled out by the redshift distributions of IRAS 60 and 100μm-selected galaxy samples (Hacking and Soifer 1 991; Fisher *et al.* 1 992).

The power law density evolution models which can fit the 60μm number counts, $\beta \sim 4$ - 7, are only consistent with FIRAS for very low values of z_{max}; z_{max} << 2.2 for the Oliver *et al.* models. This is because higher evolutionary rates are needed to fit the $z<0.5$ number counts using power law density evolution than power law luminosity evolution. Since this form of translational density evolution involves a scenario in which the fraction of galaxies having starbursts and/or AGN increases with lookback time, a low value for z_{max} is necessary, in any case, to prevent this starbursting (and/or AGN) population from becoming larger than the total galaxy population (Weedman 1990; Hacking and Soifer 1991),

The exponential luminosity evolution models fare somewhat better: both the Franceschini *et al.* (1991) model with $z_{max} = 5$ and the Oliver *et al.* model with $z_{max} = 6.9$, which can fit the local number counts with $\kappa \sim$ 2- 3, are consistent with the upper FIRAS line, though the Oliver *et al.* model is only barely consistent with the lower of tile two FIRAS lines. This difference from the power law luminosity evolution models is not surprising since exponential evolution was introduced to avoid tile high-redshift divergence of power-law evolution (Rowan-Robinson 1968).

Wright *et al.* (1993) fitted the distortion limits with a κ < 2.3 (2σ) exponential model base'd on the Beichman and Helou models, after subtracting the conservative csc$|b|$ contribution due to the Galaxy that they do not believe likely to include a significant extragalactic component (approximated by the upper FIRAS deviation line in figures 4 and 5). They estimate that this translates to an upper limit on the fraction of the baryon density converted from He to H by Such a population of evolving infrared galaxies Of < 0.8%.

The fatling dwarf model of Treyer and Silk is also comfortably consistent with the FIRAS limits, which is not surprising given that this model assigns most of evolutionary effect to dwarf galaxies at relatively low redshifts.

As noted above, all of the pure translational evolution models are limited in that they allow only translational evolution of the entire LF; they do not allow evolution of any other physical galaxy property, including the dust temperature. Most of them do not treat different galaxy types separately. Given that these models are now coming into direct conflict with the COBE results. it is clear that that the more sophisticated chemical evolution-based models are necessary to get a more realistic understanding of the integrated emission of galaxies in the far-infrared. In particular, it is important to recognise the likely importance of strong evolution of the dust optical depth in early type systems. Such models of course have their own shortcomings, most notably the fact that they have many more physical variables than can be realistically constrained by observables at present. h'on-the-less they represent the best approach in the long run since the universe contains these parameters, whether we call measure them now or not!

Figure 6 illustrates the results of the two models based on the natural chemical and photometric evolution of stellar populations and interstellar medium described above. The two models of Wang (1991b) shown in Figure 6 bracket all those displayed in his Figure 2 for $z_f = 5$. Some of these models are also strongly limited by the FIRAS distortion results, in particular the PIE models of Wang with exponentially declining star formation rate. The conflict with the FIRAS data would be lower for the lower z_f PIE model of Wang ($z_f = 2$). The accretion models of Wang are in more acceptable agreement, since they show little evolution of the dust mass with lookback time. Note that the models of Wang have not been constrained to fit the observed local universe far-infrared number counts, unlike the parametric translational models discussed above, and the models of Franceschini *et al.* (1993), The opaque model of Franceschini *et al.* (1993) is also marginally in conflict with the more stringent of the two FIRAS limits.

A constraint on the dust content and temperature of young disk galaxies has been derived by Fall and Pei (199 3), who have estimated the dust density of the damped Lyα systems, which may be the progenitors of present-day galactic. disks, from the observed reddening of quasars seen on the line-of-sight through the damped Lyα systems. From this dust density they can then estimate the contribution of these disks to the far-infrared and submillimeter background in a simple way, with the (unknown) dust temperature as the only important variable. They find limits on the co-moving dust density in the damped Lyα systems of $10^{-6} < h\Omega_{dust} < 10^{-4}$. Using the then available FIRAS and DIRBE limits, these dust densities translated to limits on the dust temperature in the disks of < 60K and < 25K for $h\Omega_{dust} = 10^{-6}$ and 10^{-4}, respectively, based on an integration of the damped Lyα systems between redshifts of 2 and 3, where they are observed. The newer FIRAS limits of Mather *et al.* (1993) would lower these temperature limits somewhat. This is an interesting technique, though it is limited by definition to low optical depth lines-of-si.ght through the foreground systems, thus can tell us little of any denser star forming regions in young disk galaxies. It can also tell us nothing of the dust masses and temperatures in ellipticals and SOS at high redshift, and these are the systems that are most likely to be the most important far-infrared emitters at early epochs,

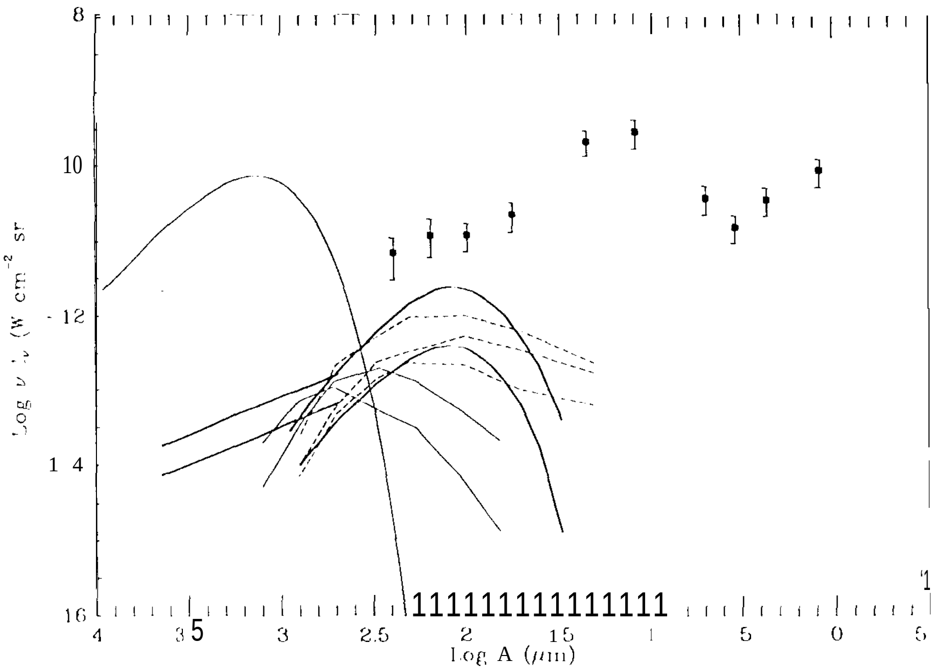

Figure 6. Comparison of various models for the integrated light of galaxies and protogalaxies to the COBE data. Heavy solid lines - Wang (1991b) $z_f = 5$ PLE model with exponentially decreasing star formation rate *(upper)*, $z_f = 5$ accretion model with constant star formation rate (lower). Dashed lines Franceschini *et al.* (1993) population synthesis no-evolution (lower), moderately opaque (middle) and opaque (upper) models. Light solid lines Franceschini *et al.* (1991) protogalaxy models with $z_f = 4.3$, $\Delta z = 0.3$ (lower), $z_f = 2$ $\Delta z = 0.1$ (upper).

Some additional constraints on evolving galaxy models can be sought at other wavelengths. In the radio a strong correlation in evolutionary behavior may be expected because of the well-known strong correlation between far-infrared and radio fluxes for most types of radio-quiet galaxies (*eg.* Helou, Soifer and Rowan-Robinson 1985). A historical anecdote is of interest here. Far-infrared evolution studies are presently based on IRAS data, and when IRAS was launched few people dreamed it would be sensitive enough to tackle cosmological questions realistically! in fact what motivated Perry hacking to address this question for his thesis (Hacking 1987; Hacking, Condon and Houck 1987) was the realization that if, because of the radio-infrared correlation, galaxies evolved as much in the far-infrared as they apparently do at cm radio wavelengths ($L \propto (1+z)^{\sim 4}$, Condon 1984) then such strong evolution should be detectable by IRAS, even though it only probed to modest redshifts ($z \lesssim 0.1$). The result of Hacking's study was the conclusion that the faint IRAS 60μm counts could be fitted reasonably well with the same model that was found to best fit the counts for the sub-millijansky radio source population (it. the non-active galaxy radio source population) by Condon (1 984).

Similar conclusions have been reached by other authors Using different models (*cg* Danese *et al.* 1987; Treyer and Silk 1993; Franceschini *et al.* 1993), therefore it seems clear that in the relatively local universe at least, the radio and far-infrared number counts and redshift distributions of non-active galaxies can be used together to constrain evolutionary scenarios. Unfortunately, for cosmological background studies the radio wavelength region is considerably less interesting that the far-infrared, as Malcolm Longair describes eloquently elsewhere in this volume.

There has been some work addressing the implications of evolving far-infrared bright galaxies to the X-ray background (Weedman 1990; Griffiths and Padovani 1990; Lonsdale and Harmon 1991; Treyer and Silk 1993). These studies conclude that the simplest parametric models which fit the far-infrared number counts can produce 50 to 100% of the soft X-ray background. Since much, if not all, of the soft X-ray Background seems to be due to AGNs, the actual contribution from starbursting infrared-bright galaxies must be no more than 50% and probably lower. This constraint, is likely to prove interesting as evolving models become more sophisticated.

3. PRIMEVAL GALAXIES AND THE FAR-INFRARED BACKGROUND

Searches at optical wavelengths for primeval galaxies using the Lyα line have not been successful. although systematic efforts over large ranges in volume and redshift have been going on for many years. An elusive and still hypothetical creature a primeval galaxy is usually defined by its hunters as an early type galaxy going though a dramatic initial star formation event, perhaps much like the luminous starburst galaxies we see in the local universe. A good recent review of the subject is given by Djorgovsky and Thompson (1 992). There are several possible explanations for this lack of success. One is that primeval galaxies must lie beyond a redshift of about 10, which is the approximate limit of large scale searches to date, a result that would be consistent with a baryonic dark matter model with primeval isocurvature fluctuations (Peebles 1987). Alternatively, it may be that the dark matter models in which galaxies grow much more recently by gravitational instability out of a scale-invariant spectrum of primeval adiabatic density fluctuations are correct. However, the most sensitive searches are now coming into conflict even with the predictions of cold dark matter galaxy formation simulations such as those of Baron and White (1987). Finally it may be that if primeval galaxies do exist, they are sufficiently dusty that the Lyα photons are extinguished and much of the energy of the object appears at far-infrared wavelengths (*eg.* Kaufman and Thuan 1977, van den Bergh 1990).

Two recent far-infrared/submillimeter PG models are those of Djorgovsky and Weir (1990) and Franceschini *et al.* (1 991). The model of Djorgovsky and Weir was actually designed to fit the 700μm excess emission over the CMB claimed to be detected by Matsumoto *et al.* (1 988). That excess has now been shown to be non-existent by COBE (Mather *et al.* 1990), however the 1110(1 ('1 is still of interest for far-infrared bright PGs in general. Based on the observed spectral energy distributions of the nearby far-infrared bright galaxies M82 and Arp 220, the model had a range of possible initial mass functions and burst timescales of 10 to 200 Myr. The models were constrained not to exceed the formation of a solar metal abundance during the burst phase. The numerical results are not directly applicable to the situation I am discussing here, however Djorgovsky and Thompson (1992) used the model to conclude that the then available COBE limits ruled out more than a few percent of the stars in ellipticals and the bulges of spirals having been formed in dusty PGs, unless the redshift corresponding to the epoch of galaxy formation is less than $z_f = 3$, and/or the dust is unusually warm.

The model of Franceschini *et al.* (1991) is also based on the spectral energy distributions of local star forming galaxies, and they constrained the energy output to be that required to produce a solar metal abundance in 2 x 10^8 years. Their resulting models for formation epochs of $z_f = 2$ and 4.3 are shown in Figure 6, where it may be seen that, as concluded by Djorgovsky and Thompson, FIRAS strongly limits models with even moderate formation redshifts and dust temperatures like those of local universe starburst galaxies.

3.1. IRAS F10214+4724 - A Possible Protogalaxy

The conclusion one may draw from the models described above is that a scenario in which most galaxies went through a dusty early phase similar to local starburst galaxies may be in conflict with the FIRAS limits. However, on the other side of the coin there is some recent evidence in favor of the existence of large amounts of dust in galaxies at early epochs, and possibly even one example of a dusty PG: the extremely luminous galaxy IRAS F10214+4724 at z=2.286 disc. overed by Rowan-Robinson *et al.* (1991). This galaxy is arguably the most luminous object in the universe with a luminosity of $10^{14} h^{-2} L_\odot$ (h=H_0/100 km/s/Mpc; q_0= 0.5), and a dust mass estimated from submillimeter observations of ?-.5 X $10^8 h^{-2} M_\odot$ (Rowan-Robinson *et al.* 1993; Downes *et al.* 1992). Evidence for large masses of dust has also been found in several high redshift quasars (Andreani *et al.* 1993).

The controversy over the interpretation of F10214+4724, as for lower redshift ultraluminous infrared galaxies, concerns the dominant source of the extremely high far-infrared luminosity detected by IRAS. There is little doubt that both a luminous starburst and a non-stellar active nucleus are present in the source. There is abundant evidence that F10214+4724 is a primeval galaxy undergoing rigorous star formation, including $\sim 10^{11} h^{-2} M_\odot$ of molecular gas (Solomon, Downes and Radford 1992), a UV-to-radio continuum energy distribution which is most simply interpreted as a powerful star burst (Rowan-Robinson *et al.* 1993; Mazzei and De Zotti 1993), and a radio source which is extended on a scale of about $2.5 h^{-1}$ kpc (Lawrence *et al.* 1993). Likewise, there is substantial evidence for an embedded AGN: high excitation emission lines (Rowan-Robinson *et al.* 1991), and strong polarization (Lawrence *et al.* 1993). In addition, new results from near-infrared (rest-frame optical) spectroscopy show [NII]/Hα and [OIII]/Hβ emission-line ratios to be typical of those found in type 2 Seyfert galaxies (Eisenhardt *et al.* 1993).

The near-infrared (rest-frame optical) continuum morphology observed using a 256^2 InSb array on the Keck telescope shows at least 3 continuum components that appear to be physically associated over a physical scale of $25 h^{-1}$ kpc (Matthews *et al.* 1993), suggesting a small cluster since each object is more luminous in the rest frame r band than a local L* galaxy, and the main, southern object has almost 100 L* in rest frame r. A number of faint sources (K>21 mag) are also seen within 20" of the central source that may be galaxies in an associated cluster. This image is reproduced in Figure 7. The Keck results also show that the brightest Hα source is now resolved on a scale consistent with that of the radio source, (0".5 $\sim 2.5\,h^{-1}$ kpc), supporting the star formation origin for the Hα emission.

Can any protogalaxy model plausibly explain the tremendous luminosity of this object? It is clearly enriched in heavy elements already, as evidenced not only by the emission line spectrum which includes lines of C, N, Ne and Mg, but also by the presence of the dust itself, and this enrichment must also be explained by any plausible model. In particular, must the dust have been created in an earlier generation of stars? If the dust was created in the envelopes of evolved stars, as may be the case for much of the dust formed in our galaxy at the present epoch, then we must be seeing F10214+4724 at an age of at least 1 Gyr.

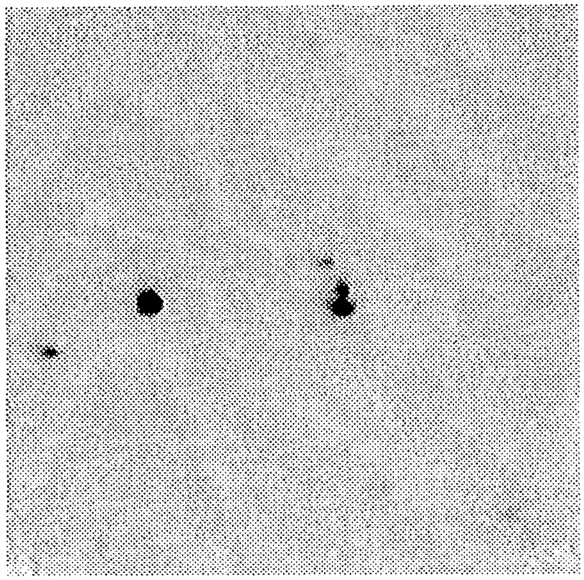

Figure 7. Image of F10214+4724 at 2.2μm from Matthews *et al.* (1993). The object is just right of center in this 40" x 40" image.

Elbaz *et al.* (1992) have developed starburst models for F10214+4724. They found that a model with a bimodal initial mass function (IMF) can achieve both the very high observed L/M_{gas} ratio of 750 $L_\odot/M_\odot$ and the strong enrichment, reaching $Z_{Fe,C,O,Si} > Z_\odot$ and $M_{dust} < M_{metals}$, in less than 10^8 years. Hamann and Ferland (1993) have developed detailed chemical evolution models for QSOs, also concluding that high metallicities can be reached rapidly: $> 10 Z_\odot$ in < 1 Gyr. The model of Elbaz *et al.* has a bursting component with a lower mass limit to the IMF of 3 $M_\odot$ and a star formation rate of 6200 $M_\odot$/yr. They were unable to achieve a fit with a single IMF. The source of the dust in the Elbaz *et al.* model is not evolved stars but supernova remnants. While it is not known whether supernova remnants can be responsible for significant amounts of dust formation, there is evidence that SN1987A has produced 0.1 $M_\odot$ of dust (Dwek *et al.* 1992). At a supernova rate of $1.25\times 10^{-12}(L/L_\odot)$/yr (Solomon, Radford and Downes 1992) for 108 years, remnants like 1987A could easily produce the the estimated dust mass of $2.5\times 10^8 h^{-2}$ M C).

Mazzei and De Zotti (1993) have successfully modeled the spectral energy distribution of F10214+4724 using the population synthesis models of Mazzei *et al.* (1993) (see Figure 3). They find a good fit at, an age of 1 Gyr (for H = 50 km/s/Mpc; q_0 = 0.5) with a star formation rate of 3×10^4 $M_\odot$/yr; a fit with a much younger age is also possible. Mazzei and De Zotti show t.list

F10214+4724 could plausibly fade to a z = 0 elliptical with bolometric luminosity less than 10^{13} $L_\odot$.

3.2. A Protogalaxy Model Based on IRAS F10214+4724

The models described above for the contribution to the far-infrared background by infrared-bright protogalaxies, those of Djorgovsky and Weir (1990) and Franceschini *et al.* (1991), are based on the spectral energy distributions of *local universe* starburst galaxies. If it is truly powered by star formation, then F10214+4724 provides us with the opportunity of using a high redshift object with known luminosity and spectral energy distribution as a template for protogalaxies, thus eliminating the uncertainties introduced by assuming that local universe objects are good analogs of protogalaxies, or by adopting a model spectral energy distribution with an assumed dust temperature and luminosity. It also allows us to avoid the large K-corrections involved in redshifting local templates to cosmological distances.

I have therefore developed a simple model to determine the contribution to the far-infrared background of a population of galaxies, forming with a protogalactic burst like that observed in F10214+4724. If a QSO contributes significantly to the luminosity of F10214+4724 then the model predictions can be treated as upper limits to the background emission unless the coeval existence of a QSO with the starburst is a common feature in the formative stages of all ellipticals (*cf.* Hamann and Ferland 1993 and references therein).

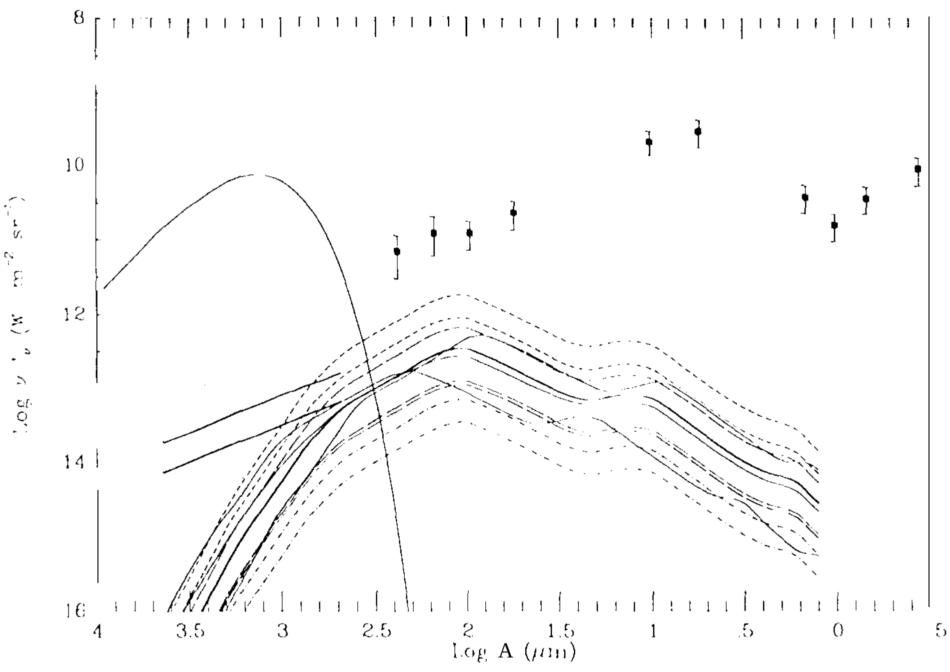

Figure 8. Protogalaxy model predictions compared to the COBE data. Baseline model of Table 2 (heavy solid line); other lines show effects of changing other parameters: redshift range (light solid lines): z_f = 5 - 10, ? - 10, 1.5- 2.5; cosmology (short dashed lines): $\Omega = 0$ and $H_0 = 100$ (upper line) and 50 (lower line); LF (long dashed lines): Tamman *et al.* (lower line), Franceschini *et al.* (middle line), Efstathiou *et al.* (upper line includes disk galaxies); *f* (dot-dash lines): *f* = 50 (upper line), *f* = 100 (lower line).

Table 2: Protogalaxy Model Based on IRAS F10214+4724

Parameter	Range Considered	Baseline Model
H_0	50, 100	50
Ω	0, 1	1
z_f	1.5-10	2 - 5
Δt	1.0 to 2.0 $\times 10^8$ yrs	10^8 yrs
f	10-100	10
Luminosity Function	Shanks *et al.* 1990, Es only	Shanks *et al.* 1990
	Efstathiou *et al.* 1988, all galaxies	
	Franceschini *et al.* 1988a, Es only	
	Tammann *et al.* 1979, Es only	

luminosity Function (H_0=100)	ϕ^* (# Mpc^{-3})	M* (mag.)	α
Shanks *et al.* 1990	0.0096	-19.00	-0.07
Efstathiou *et al.* 1988	0.0156	-19.68	-1.7
Franceschini *et al.* 1988a	0.0032	-19.60	-1.0
Tammann *et al.* 1979	0,0031	-19.45	-0,77

I assume all galaxies have an SED of similar shape to F10214+4724. Galaxies are assigned luminosities according to a luminosity function. The variable parameters of the model are the cosmology, the formation redshift z_f, the burst duration δt, the luminosity function, and the factor, f, by which F10214+4724 is assumed to be brighter or fainter than the characteristic luminosity at the knee of the luminosity function, $L_{F01214} = f\, L^*$, where the luminosity function is given by $\phi(L)dL = \phi^*(L/L^*)^{\alpha} e^{-L/L^*} d(L/L^*)$ (Schechter 1976). Here ϕ^* is the characteristic space density. Four different local luminosity functions were considered. Note that using a local luminosity function to define the distribution of galaxy luminosities at high redshift is equivalent to adopting a mass function, as long as the evolutionary behavior with lookback time of the L/M ratio does not vary greatly with galaxy mass.

The range of parameters considered is given in Table 2. For most models the luminosity function was restricted to elliptical galaxies only, since spirals are not expected to have formed with a dramatic initial burst. The factor f was restricted to 10 or higher because F10214+4724 is undoubtedly a very rare and unusually luminous object. Estimates for the expected surface density of protogalaxies are in the range 10^3 to 10^5 per square degree, depending on the cosmology, the epoch of formation and the duration of the bright phase (*eg.* Djorgovsky and Thompson 1992). From the detection statistics we can estimate a surface density of objects like F10214+4724 of 1.5×10^{-3} per square degree; allowing a factor of ± 10 on this estimate since the statistics are very crude (only one object has been detected, and that very close to the detection limit of the IRAS survey) it follows that objects like F10214+4724 are at least 10^5 times less numerous that "typical" primeval galaxies. For a Schechter LF, this translates roughly to $f > 10$.

Full details of the model are given in Lonsdale (1994, in preparation). Figure 8 summarises the results of the models compared to the data of Figure 1. Figure 9 illustrates the blue and K-band number counts for the model population of F10214-like protogalaxies, compared to observational data.

The low Ω protogalaxy models shown in Figure 8 are in conflict with the FIRAS limits. The $\Omega = 1$ models are mostly consistent with FIRAS except the model using the Franceschini *et al.* (1988a) LF including all galaxies (not only ellipticals), which is in conflict with the more stringent FIRAS limit, and the high redshift range model which is only marginally consistent with the stringent limit. None of the models are in conflict with the current DIRBE observations. Therefore, basically the entire range of parameter space that has been explored is allowed for a high Ω universe. An acceptable fit for a low Ω universe would require $z_f = 5$ or lower, and/or $f < 10$, and/or a burst duration shorter than 2×10^8 yrs.

The number count predictions are small compared to the observed counts, therefore it is not surprising that only one object like F10214+4724 has so far been discovered by serendipitous spectroscopic follow-up studies of faint field galaxies. Systematic surveys of 2.2μm-selected objects in the 15 to 18th magnitude range, where such objects could account for 10% of the sample, might be the most fruitful.

To summarise, the main result of the model presented here is that it is quite possible that a large fraction of the light of forming galaxies is hidden in the far-infrared wavelength region. Thompson and Djorgovsky (1992) and Franceschini *et al.* (1991) concluded from their models that to hide galaxy formation in the far-infrared would require quite low values of z_f ($z_f < 5$) and/or warm dust temperatures. Both of these requirements are the result of the FIRAS limits. The F10214+4724 model is consistent with these results because this object does indeed contain relatively warm dust: Downes *et al.* (1993) derive a dust temperature of 80K for the far-infrared/submillimeter emission. Thus this model demonstrates the plausibility of a significant background from protogalaxies in the far-infrared most convincingly since it based on the real SED of a dust-rich, star-forming galaxy with known luminosity at a known (cosmological) redshift, rather than on a local universe analog, or a theoretical thermal spectrum. In particular, the $\lambda > 100\mu$m spectral shape, which is a critical constraint compared to the FIRAS observations, has been directly measured for this object.

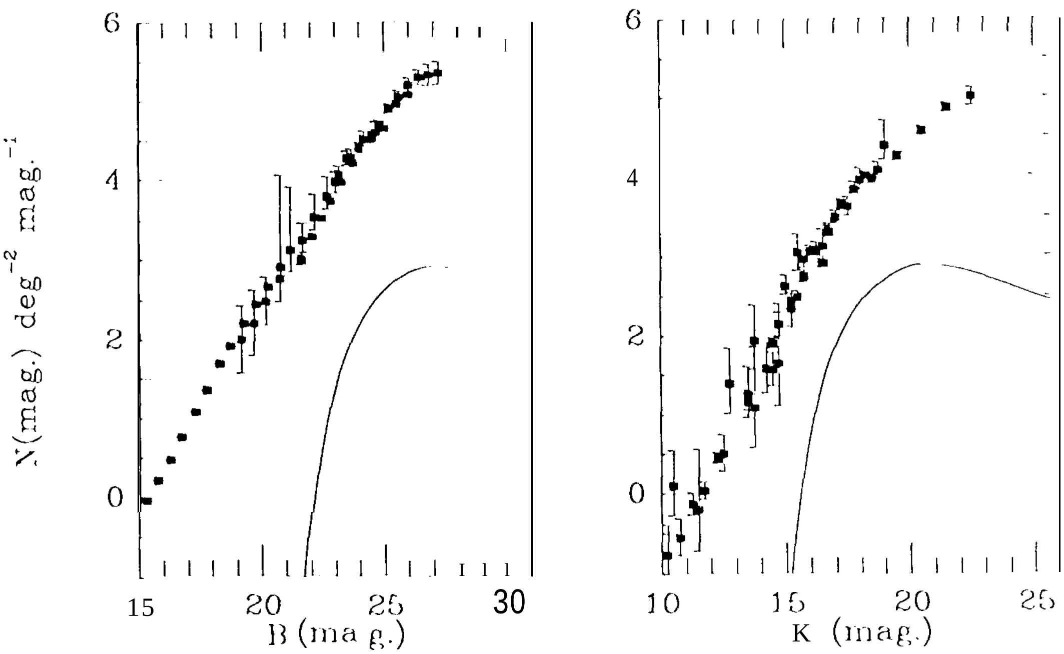

Figure 9. Blue and K-band galaxy number counts compared to the prediction from the baseline protogalaxy model (see Table 2). The references to the data can be found in Chokshi *et al.* (1993).

4. THE FUTURE IN SPACE: DIRBE, 1S0 ANI) S]]{ 'J']"

Where do we go next to test these ideas? Obviously we anxiously await the revised, foreground-subtracted, DIRBE limits: if the team is able to reliably subtract the foregrounds to levels approaching the design sensitivity of $\nu I_\nu = 10^{-13}$ W cm^{-2}sr^{-1} (Boggess *et al.* 1992), which is about 1% of the foreground emissions, then they can expect to detect or rule out most of the predicted contributions to the background by evolving galaxies and infrared-bright protogalaxies shown in Figures 4, 5, 6 and 8.

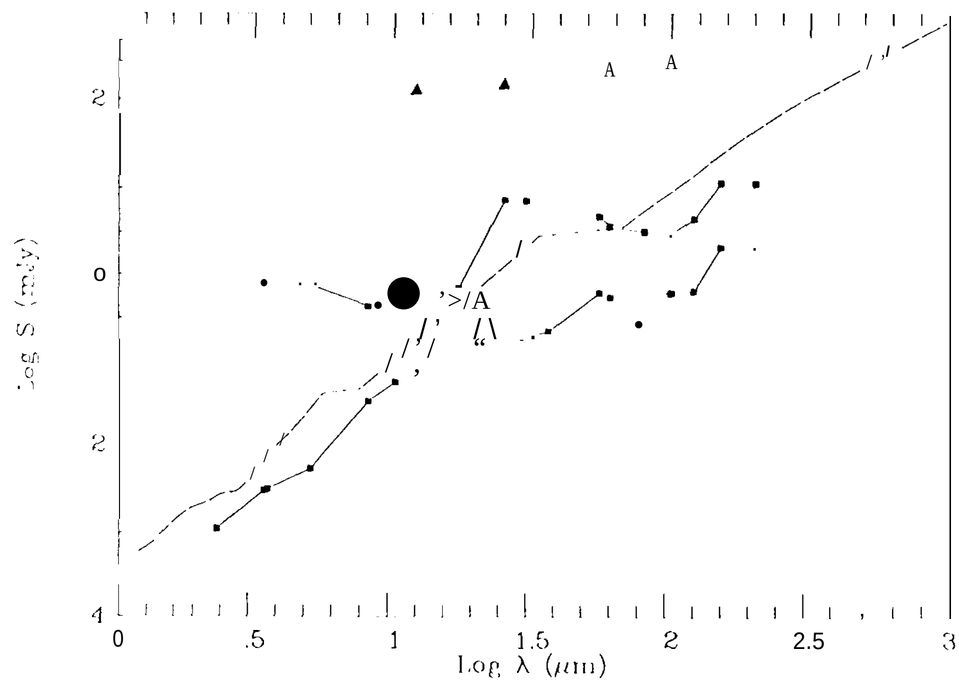

Figure 10. 1S0 and SIRTF background-limited point source sensitivities, 50 in 500 seconds (upper and lower solid lines, respectively) (E. Young, private communication), compared to the IRAS Faint Source Catalog sensitivity limits (90% completeness limits for the most sensitive 10% of the sky; filled triangles), and to IRAS 1'10214-{ 4724 moved to a redshift of 10 (H_0= 50, Ω= 1).

Although the nineties was heralded as the decade of the infrared by the Bahcall committee, the poor funding situation at present has delayed our hopes for the next generation US infrared mission, SIRTF, into the next century. Meanwhile the European sate'llitc 1S() is due to launch in late 1995. Both ISO and SIRTF are observatory class instruments, differing from the survey instruments IRAS and COBE in having small beams and fields-of-view. Thus they are optimised for point source work and fluctuation analyses much more than direct background measurements, although S11{'1'1" may be able to match the surface brightness sensitivity of 1)11{ 111'; with considerable work. SIRTF will be especially important for cosmological studies because its detector technology will be frozen at a much later elate than that of 1S(), and because it has larger arrays than 1S0. Figure 10 compares the expected point source sensitivities of 1S() and SIRTF compared to IRAS F10214-| 4724 removed to z= 10.

SIRTF may hope to resolve all of any background that DIRBE may detect in the near-il~frarc(] window near 3μm. A calculation by E. Wright (M. Werner, private communication) shows that the minimum expected integrated intensity at $3.5\mu m$ due to galaxies is about $\nu I_\nu = 3.4\times10^{-13}$ W/cm^2/sr. This is derived from the measured extragalactic number counts at $2.2\mu m$ (Gardner *et al.* 1993), assuming a temperature of 2000K to estimate the $2.2\mu m$-$3.5\mu m$ color. Comparing this to the hoped-for ultimate DIRBE sensitivity of about 10^{-13} W/cm^2/sr it is clear that the background due to this known population will be detected by DIRBE. At an intensity of 3.4x 10^{-13} W/cm^2/sr, the number of faint galaxies per 0.7 degree DIRBE beam is about 1.2 X 10^5, giving an average separation of 10 arcsec. This is within reach of the 1 arcsec beam of SIRTF to resolve. To reach the required limit of 21.6 msg. at $3.5\mu m$ with SIRTF will require an integration time of about 10,000 seconds.

A similar calculation at $60\mu m$ based on a local $60\mu m$ luminosity function and exponential evolution with $\kappa=1.5$, $H_0=75$, indicates that about 60% of the predicted background above an anticipated DIRBE limit of about 2×10^{-13} W cm^{-2} sr^{-1} will be resolvable by SIRTF, assuming a SIRTF confusion limit of shout 0.1 mJy at this wavelength (Wright 1993).

Franceschini *et al.* (1991) have calculated the fluctuations expected in the 0.7 degree DIRBE beam due to their model evolving galaxy populations. Fluctuations $\Delta I_\nu/I_\nu$ range from 2% at $280\mu m$, through 4-7% at 25 to $100\mu m$ and rise to 50% at 2.21/in. These high values at short wavelengths are dominated by bright stars in the galaxy. The main limitation at the longer wavelengths will be confusion noise due to galactic *cirrus emission* (Gautier *et al.* 1992).

5. CONCLUSIONS

The very sensitive new FIRAS CMB-deviation limits severly constrain parametric translational models for galaxy evolution at wavelengths longer than $500\mu m$. It follows that the evolutionary rates for infrared-bright galaxies implied by such models in the local universe cannot continue to cosmological redshifts for the class as a whole, unless exponential luminosity evolution is adopted. Most likely the current generation of parametric models is too simple in approach to adequately model this complex situation; in particular the likely strong evolution of the dust content of early type galaxies is not taken into account by these models.

The analytical chemical evolution models of Wang (1991a,b) address the evolution of the dust content. His accretion models are not in conflict with the current COBE limits but the prompt initial enrichment model is closely constrained. Similarly, the models of Franceschini *et al.* (1993). which are based on the closed box population synthesis models of Mazzei *et al.* (1992, 1993) incorporating chemical and dust evolution, are presently consistent with, but close to being constrained by, the COBE data. The simulations of deep galaxy fields of Chokshi *et al.* (1994, in preparation), which are also based on the population synthesis models of Mazzei *et al.* (1993), are also likely to provide interesting constraints (sew Chokshi *et al.* 1993).

The FIRAS limits also constrain models for infrared-bright protogalaxies. If a significant fraction of the light created in primeval galaxies emerges in the far-infrared due to large dust optical depths then the FIRAS limits restrict the epoch or formation to $z < 5$ for low Ω, and/or require relatively warm dust temperatures. A model based on the luminous, warm, z= 2.286 IRAS galaxy F10214+4724 can satisfy these requirements.

DIRBE will be able to detect. the backgrounds expected from evolving galaxies and from infrared-bright protogalaxies, unless these objects are much less dusty than the models assume.

ISO and SIRTF will be able to detect objects like F10214+4724 to redshifts approaching 10. SIRTF will be able to resolve all of any background that DIRBE can expect to detect at 3 microns. and most of a DIRBE background at $60\mu m$.

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